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Local and System Exergy Losses in Cogeneration Processes

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Abstract

In cogeneration processes a major product appears as well as one or more by-products. The cumulative consumption of primary non-renewable exergy burdening the major product can be determined by means of the principle of avoided expenditures, assuming that the utilization of by-products eliminates the exergy consumption in the subprocess replaced by that utilization. The mentioned principle makes it usually possible to determine the consumption of raw materials and semi-finished products burdening the major product. That determination is, however, not possible if the by-product replaces some imported material, because such material burdens with the exergy consumption the total domestic production system.

Keywords: Cogeneration process, cumulative exergy, imported materials

1. Introduction

Local exergy losses appear in particular links of the considered process because of the irreversibility of their internal phenomena. However, exergy losses appear also in preceding processes delivering semi-finished products and energy carriers to the considered installation. Cumulative exergy consumption connected with the total production chains of the delivered semi-finished products and energy carriers represent system exergy losses burdening the considered installation.

The determination of local and system exergy losses is not difficult in single-purpose production processes. However in the case of cogeneration processes producing more than one useful product, that determination may be difficult, especially if there are one or more imported semi-finished products.

2. Cogeneration processes

A multi-purpose process belongs to cogeneration processes if one major product can be defined, which determines the location and production rate of the considered installation. Every additional useful product represents a by-product if it replaces some product obtained in an individual production process. For example, a steam heat-and-power plant delivering heat as a major product, also produces electricity which replaces some part of electricity delivered from a specialized power plant. Hence, electricity from an HP-plant is a by-product of that plant.

The exergy consumption burdening the by-product can be determined by means of the *principle of avoided expenditures*, first published by Wagner (1962) and later independently introduced in the USA as a state deed PURPA (US DOE 1978). According to the mentioned principle, the utilization of the by-product eliminates the financial (or exergetic) expenditures in the process replaced by that utilization. The amount of the replaced product should be calculated by means of the *replacement ratio* s_{iu} expressed in units of the replaced product per unit of the by-product.

3. Cumulative exergy consumption

Nature is a source of primary non-renewable exergy used as raw-material or energy carrier in all human production processes. Cumulative exergy consumption (CExC) expresses the total consumption of primary non-renewable exergy in all subprocesses leading to the considered product.

The concept of CExC is similar to that of cumulative energy consumption, called "energy cost", initiated by Chapman, Learch and Slesser (1974) and analyzed by Boustead and Hancock (1979).

Exergy does not satisfy the law of conservation. Every irreversible process causes irrecoverable exergy losses, closing the exergy balance. However, when calculating the value of CExC, the principle used in the calculation of cost can be applied: the output cost results from the sum of input costs.

Similarly, CExC can be calculated by means of a set of linear balance equations (Szargut and Morris, 1987) based upon the statement that the CExC-value of the product of some considered process results from the CExC-values burdening its input semi-finished products and the consumed exergy (*Figure 1*). The mentioned balance equation is related to the unit (1 kg of material, 1 kJ of electricity or of useful heat) of the major product:

$$b_j^* + \sum_u f_{uj} b_u^* = \sum_i a_{ij} b_i^* + \sum_u a_{uj} b_u^* + \\ + \sum_r a_{rj} b_r^* + \sum_\beta a_{\beta j} b_\beta \quad (1)$$

where $b_j^*, b_i^*, b_u^*, b_r^*$ = specific CexC-value burdening the major product of the *j*th and *i*th process, the *u*th by-product and the *r*th imported semi-finished product, kJ/kg, kJ/kJ,

$a_{ij}, a_{uj}, a_{rj}, a_{\beta j}$ = coefficient of consumption of the *i*th and *r*th semi-finished product, *u*th by-product and βth natural resource per unit of the *j*th product,

f_{uj} = coefficient of the by-production of the *u*th by-product per unit of the *j*th major product,

b_β = specific exergy of the natural resource extracted from nature

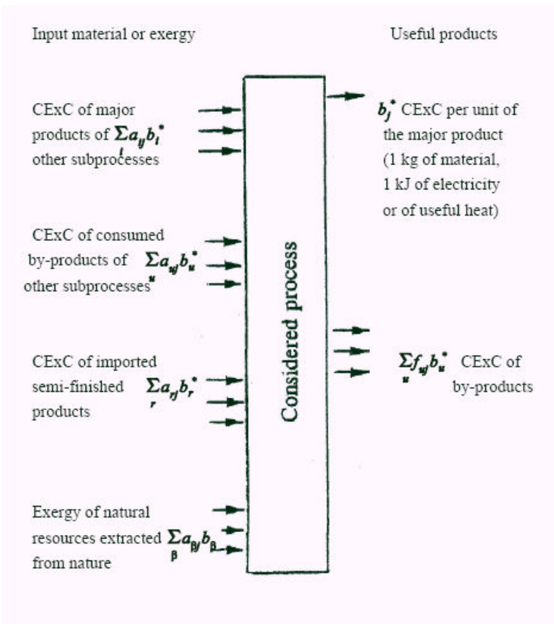

Figure 1. Diagram of the calculation of CExC

The terms representing the production and consumption of the by-products can be replaced by terms containing CExC of the *i*th major product replaced by the *u*th by-product:

$$f_{uj} = \frac{f_{ij}}{s_{iu}}, \; a_{uj} = \frac{a_{ij}}{s_{iu}}, \; b_u^* = b_i^* s_{iu} \quad (2)$$

where s_{iu} denotes the replacement ratio in units of the *i*th major product replaced by a unit of the *u*th by-product.

The solution of the set of Equation (1) determining the CExC values is usually unavoidable only in the case of main energy carriers and semi-finished products. Other materials and semi-finished products can be analyzed by means of the sequence method (Szargut 2001), (cf. *figure 2*). The values determined in this way are cited in papers and books (Szargut 2005). Knowing those values one can apply Equation (1) separately for other considered products. Usually the CExC values of domestic semi-finished products are known.

In the cogeneration process the application of Equation (1) requires a selection of the replaced subprocesses. It is impossible to determine the subprocess replaced by the utilization of the by-product when the by-product replaces some imported material (or energy); for example, cogenerated blast-furnace gas or converter gas replaces imported natural gas.

The financial means for import are gained by export. Therefore, it may be assumed that the cumulative exergy of imported goods results from the financially equivalent average cumulative exergy of exported goods (Szargut 1987):

$$b_r^* = b_d^* D_r = D_r \frac{\sum_e S_e b_e^*}{\sum_e S_e D_e} \quad (3)$$

where: b_d^* = average value of CExC per monetary unit of export,

D_r, D_e = monetary value per unit (1 kg of material or 1 kJ of electricity) of the imported and exported good,

S_e, b_e^* = amount of units of the annual export of *e*th good and its specific cumulative exergy.

When applying formula (3), the iterative procedure must be applied, because in the production of exported goods imported semi-finished products can also be used. The mentioned iterative calculations connected with Polish export have been performed by Stanek (2001).

TABLE I. CUMULATIVE EXERGY EFFICIENCY OF THE PRODUCTION OF SOME MATERIALS

Material	Cumulative exergy efficiency of the production %
Glass (from natural raw materials)	0.8
Oxygen for metallurgy (not compressed)	1.4
Nickel (from ore concentrates)	1.6
Copper (electrolytic from Cu_2S-ore)	3.1
Led (from natural ore)	3.5
Cement (wet method, medium rotary kiln)	6.2
Aluminium (from Al_2O_3, electrolytic method)	13.2
Steel products, cold rolled	14.9
Sulfuric acid (from sulfur)	15.0
Tin (from concentrate containing 20% Sn)	15.4
Steel pipes	16.0
Paper (from natural timber)	18.7
Steel products, hot rolled	19.0
Sinter of iron ore (from natural ore)	21.0
Cellulose (from timber, waste products used as fuel)	27.4
Methanol	30.1
Converter steel (15% scrap)	30.7
Electric steel (liquid, 100% scrap)	35.4
Pig iron, liquid (from sinter with 32,5% Fe)	40.0
Ammoniac (from semi-combustion of natural gas)	41.1
Pig iron (from ore with high hematite content)	44.0
Polyethene (from crude oil, small density)	52.5
Benzene (from crude oil)	68.1
Paper (from wastepaper)	74.3
Metallurgical coke	78.5
Motor oil	80.6
Lignite	92.3
Hard coal (extraction and transportation)	93.1
Steel scrap	96
Natural gas, domestic	97
Natural gas, imported (year 2000)	130

4. Cumulative exergy efficiency and system exergy losses

The ratio of exergy of the useful product to its CExC-value expresses the cumulative exergy efficiency CFxE:

$$\eta^*_{B\,j} = \frac{b_j}{b^*_j} \tag{4}$$

The values of CExE of production of typical materials have been gathered in TABLE I (Szargut 2005).

The difference of the denominator and numerator in Equation (4) expresses the cumulative exergy loss CExL in all the steps of the production chain leading from primary exergy to the considered useful product. CExL consists of the local exergy losses $\delta b_{l\,j}$ appearing in the last subprocess of the considered production chain and system exergy losses $\delta b^*_{s\,j}$ expressing the cumulative exergy losses in the production of semi-finished products:

$$\delta b^*_j = b^*_j - b_j = \sum_l \delta b_{l\,j} + \sum_s \delta b^*_{s\,j} \tag{5}$$

The calculation of local and system exergy losses has to indicate the possibilities of economy of the primary feeding exergy. However, the analysis of the mentioned exergy losses is not expedient in systems utilizing renewable natural exergy. In that case the economy of the natural renewable exergy may be necessary only if the limitation of its regeneration velocity hampers its utilization.

TABLE II. LOCAL AND SYSTEM EXERGY LOSSES IN THE SET OF A BLAST FURNACE

Name	Consumption per 1 kg of pig iron		Cumulative exergy consumption kJ/kg,kJ/mol	Cumulative exergy efficiency	Exergy loss kJ/kg pig i.
	gross	net			
Local losses					
blast furnace	C	C	C	C	2275
blast heaters	C	C	C	C	995
set of blast compression	C	C	C	C	516
System losses					
coke	0.423 kg/kg	0.423 kg/kg	46.1 kJ/kg	73.2%	5813
iron ore	0.206 kg/kg	0.206 kg/kg	0.43 kJ/kg	20%	71
sinter	1.594 kg/kg	1.594 kg/kg	6.8 kJ/kg	21%	8562
oxygen	2.45 mol/kg	2.45 mol/kg	284 kJ/mol	1.4%	685
hard coal	3890 kJ/kg	3890 kJ/kg	1.08 kJ/kJ	93%	294
electricity	56.8 kJ/kg	56.8 kJ/kg	3.6 kJ/kJ	28%	148
blast furnace gas used beyond the set	-4380 kJ/kg	-3723 kJ/kg	624 kJ/mol	130%	1117
Total					20426

From Equation (1) it results that the production of useful by-products decreases the CExC burdening the main product of the cogeneration process.

Equation (4) can be used to calculate the cumulative exergy efficiency of the delivery of imported semi-finished products. When the import price is advantageous, or when in the export the agricultural or high-tech products prevail, the exergy of the imported semi-finished product is higher than the average cumulative consumption of exergy burdening the domestic products exported to gain financial means for the import. In that case the exergy efficiency of delivery of the imported semi-finished product is higher than 100% and the connected system exergy loss is negative. The utilization of imported material (or energy) decreases the overall domestic CExC, hence, in the considered case the import decreases the degree of depletion of domestic non-renewable exergy resources.

In the considered case, by-production denotes a negative system exergy loss, but the CExL burdening the imported material (or energy) is also negative. Two negative signs denote the sign "plus". Hence, in that case the utilization of the by-product leads to an increase of CExC of the considered major product. The advantage of the utilization of such a by-product appears in the subprocess consuming the mentioned by-product.

For example, the blast-furnace gas produced as a by-product of pig iron fabrication, replaces partially the natural gas feeding the metallurgical heating ovens. The imported natural gas closes the demand for gaseous fuels of the country. If its import price is advantageous, the CExL burdening that fuel is negative. Hence, the application of blast-furnace gas in order to replace the imported natural gas, incre-ases the CExC burdening the produced pig iron. The advantage of the utilization of blast-furnace gas becomes evident in heating furnaces, because it is connected there with a negative system exergy loss.

Example 1. Local and system exergy losses in the blast-furnace.

TABLE II quotes the results of the calculation of local and system exergy losses in the blast furnace set producing liquid pig iron (as the major product) and blast-furnace gas (by-product). The analyzed production set comprises the blast furnace, the Cowper heaters of blast, fueled with some part of blast-furnace gas, the blast compressor, its driving steam turbine and the boiler producing steam for the turbine. The process consumes the following semi-finished products: iron ore and sinter, coke, hard coal, electricity, technical oxygen. The produced blast-furnace gas is partially used for heating the blast. The remaining part is mainly used in metallurgical heating furnaces, where it replaces the natural gas.

The blast-furnace gas replaces the imported natural gas, closing the domestic demand for gaseous fuels. It has been assumed that the price of imported natural gas is advantageous and, therefore, CExE of its delivery exceeds 100%. The peak part of the blast-furnace gas production is burned in the steam boiler, together with the hard coal. Some amount of pulverized hard coal is injected into the zone of tuyeres of the blast-furnace (Stanek 1999).

When determining the system exergy losses one cannot assume that the production of a by-product decreases the demand for semi-finished products consumed in the blast-furnace, because the by-product replaces the imported semi-finished product which burdens the production system of all exported goods with exergy losses.

In the considered blast-furnace set, the blast is preheated to 1100°C and enriched with oxygen to a molar content of 26%. The gas fueling the Cowper heaters is not enriched with natural gas.

The replacement ratio of the chemical exergy of natural gas by blast-furnace gas is smaller than 100% (it has been assumed to be 85%, i.e. 0.1 mol natural gas per 1 mol of blast furnace gas), because the combustion of blast-furnace gas generates a larger amount of combustion gases and decreases the efficiency of heating in comparison to natural gas.

In column 3 of Table II the negative net consumption of blast-furnace gas is replaced by the exergy of natural gas.

The local and system exergy losses related to 1 kg of pig iron can be compared to the exergy of liquid pig iron 8.75 kJ/kg. The local exergy losses express the influence of the irreversibility of the internal processes in the links of the considered set. The immediate exergy efficiency of the blast-furnace set amounts to 69.8%. System exergy losses reflect the influence of the irreversibility of the production of semi-finished products. The cumulative exergy efficiency of the considered set amounts to 42.7%. Among the exergy losses, the production of sinter is a considerable item. Also the production of coke introduces considerable system exergy losses.

5. Partition of the consumption of semi-finished products and exergy losses

The analysis presented in section 4 does not indicate how cogeneration influences the consumption of semi-finished products and the exergy losses burdening the major product only. The partition of the consumption of semi-finished products and exergy losses between the major product and the by-products is possible if in the production process replaced by the utilization of by-product the same raw materials and semi-finished product as in the analyzed cogeneration process appear. If in the analyzed process the imported semi-finished products are consumed and no by-production replacing such imported product occurs, then the net consumption coefficients (Szargut 1992) can be introduced into the balance equation (1):

$$a_{ij\,N} = a_{ij} + (a_{uj} - f_{uj})\, s_{iu} \qquad (6)$$

After introducing the net consumption coefficients and omitting the imported semi-finished product the balance equation (1) takes the form:

$$b_j^* = \sum_i a_{ij\,N}\, b_i^* + \sum_\beta a_{\beta j}\, b_\beta \qquad (7)$$

Applying Equation (7) one can calculate the local and system exergy losses burdening exclusively the major product of the analyzed process.

Example 2. Local and system exergy losses burdening the production of heat in a steam HP-plant equipped with a counter-pressure turbine.

The following data have been assumed for the considered HP-plant: the energy efficiency of the steam boiler 82%, the cumulative energy efficiency of electricity production in the replaced power plant 27.6%, ratio of the produced electricity to the useful heat 0.531, heat losses in the major pipeline 15%, in the local pipeline 2% (hence the delivery of 1 GJ heat to the consumers requires the production of 1.2 GJ in the HP-plant), relative water losses in the major pipeline 0.7%, the durability of the steel pipes 10 years (hence, the consumption of steel for the replacement of the pipes 0.25 kg/GJ heat) (Szargut 1989).

An analysis has been performed for some values of the environmental temperature selected from the durability curve of that temperature, TABLE III. *Figure 2* presents a graphical scheme of the sequence calculation of CExC and CExL in the production process of useful heat. The diagram concerns the mean ambient temperature in the heating season, 2°C. The production of electricity, being a by-product of the HP-plant, has been eliminated from consideration by means of the net consumption coefficient of coal, Equation (6). That consumption coefficient may be presented in the form:

$$\dot{P}_q = \dot{P} - \frac{N_{\mathrm{el}}}{\mathrm{H_u}\, \eta_{\mathrm{E\,el}}}$$

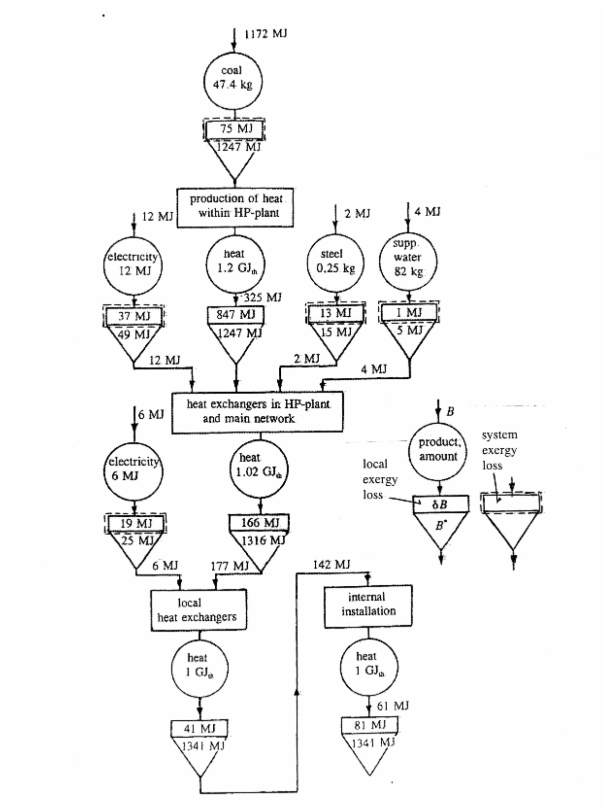

Figure 2. Sequence analysis of CExC in the process of production and delivery of heat from a steam HP-plant.

where: $\dot{P}$, $\dot{P}_q$ = total consumption stream of coal and the stream burdening the heat production only,

$\eta_{E\,\mathrm{el}}$ = energy efficiency of the replaced power plant

H_u = lower heating value of the fuel.

It has been assumed that electricity driving the network pumps is taken from the electric grid. The consumption of that electricity results in local exergy losses, and the cumulative exergy loss burdening its production belongs to the system losses. The exergy of steel used for the maintenance of the network is lost due to corrosion. Therefore, it leads to a local exergy loss. The cumulative exergy loss in the production of steel belongs to the system losses. Similarly, the exergy of supplementing water evokes local exergy losses, and the cumulative exergy loss in water preparation belongs to the system losses.

The following temperature values in the HP-plant and in heat exchangers have been assumed:

C condensation temperature of the extraction steam 104 °C,

C temperature of the hot and flowing back water in the major pipe-net 78/42°C,

C temperature of the hot and flowing back water in the local pipe-net 53/42°C,

C temperature in the heated rooms 20°C.

The cumulative exergy efficiency of the delivery of heat depends considerably on the ambient temperature.

6. Conclusions

The principle of avoided expenditures applied to analyze cogeneration processes provides a basis for calculation of the cumulative exergy efficiency of the production of the major product. In many cases, for example in the HP-plant fed with coal or lignite, the raw materials used in the cogeneration process are the same as in the process replaced by the utilization of the by-product. In such a case the principle of avoided expenditures permits also the partitioning of raw materials used in the cogeneration process into parts burdening the major product and those burdening the by-products. However, this is not always possible. When the by-product of the cogeneration process replaces some imported raw material, that material is burdened with exergy losses of all the domestic processes producing the exported goods. In such a case only the cumulative exergy efficiency of the production of the major product can be calculated.

In every production process appear not only local exergy losses caused by the irreversibility of the respective parts of the process, but also system exergy losses burdening the production of the consumed semi-finished products. When a partition of raw materials between the major product and the by-product is not possible, the system exergy loss connected with the product substituted by the by-product is negative. A more paradoxical effect can turn up when the calculated cumulative exergy consumption of exergy burdening the replaced by-product is smaller than its exergy (hence its cumulative exergy efficiency exceeds 100%). In such an exceptional case two "minus signs" meet and the system exergy loss connected with the by-product becomes positive.

TABLE III. LOCAL AND SYSTEM EXERGY LOSSES DURING THE PRODUCTION AND DELIVERY OF HEAT FROM A STEAM HP-PLANT FOR THE HEATING OF ROOMS (IN % OF THE CUMULATIVE CONSUMPTION OF COAL EXERGY)

Process	Ambient temperature ^oC					
	C20	C11	C5	+ 2	+ 6	+ 12
Local losses						
Heat production in the HP-plant	56.6	51.0	56.7	63.1	66.0	68.1
Electricity for driving network pumps	0.9	1.1	1.2	1.4	1.5	2.1
Heat transfer in major heat exchangers and heat transmission in the major network						
Heat transfer in local heat exchangers and heat transmission in the local network	9.3	13.2	13.0	12.4	12.7	13.0
Heat transfer in the internal installation	4.3	4.7	3.8	3.1	2.4	1.6
Supplementing water consumption	11.1	11.9	9.2	6.0	4.3	2.1
Steel consumption for the network maintenance	0.1	0.1	0.1	0.1	0.1	0.1
	0.1	0.1	0.1	0.2	0.2	0.2
System losses						
Supply of coal	5.1	5.2	5.4	5.6	5.8	6.2
Electricity production for driving the network pumps.......................................	1.9	2.3	2.5	2.8	3.0	4.3
Steel production for the maintenance of the network	0.7	0.9	1.0	1.0	1.1	1.2
Supplementing water preparation	0.2	0.2	0.3	0.3	0.3	0.4
Cumulative exergy efficiency	9.7	9.3	6.7	4.0	2.6	0.7

Nomenclature

a_{ij},a_{uj}	coefficient of gross consumption of the major product of *i*th process or of *u*th by-product, related to the complex of useful products of the considered *j*th process, containing a unit of its major product
b	specific flow exergy of the matter crossing the immovable system boundary, J/kg, J/mol
b^*	cumulative consumption of primary exergy per unit of the considered product, J/kg, J/mol
D_i,D_r	monetary value of the *i*th exported and r^{th} imported product
f_{ij}	coefficient of by-production of the substituted major product of *i*th process per unit of the major product of the considered *j*th process
f_{uj}	coefficient of production of the *u*th by-product per unit of the major product of the considered *j*th process
H_u	lower heating value, kJ/kg
N_{el}	electric power, kW
P	fuel consumption, kg
s_{iu}	replacement ratio in units of the *i*th substituted major product per unit of the *u*th by-product
δb^*	cumulative exergy loss burdening the total chain of fabrication of the considered product
δ	symbol of loss (δB = exergy loss)
Δ	symbol of increase (ΔB = exergy increase, ΔT = temperature increase)
η_B	exergy (exergetic) efficiency

Subscripts

B	related to exergy
E	related to energy
el	related to electricity
i, j	order number of the process and its major product
l	local
N	net value (per unit of the major product),

q	related to the heat source
s	related to the system
u	order number of the by-product
β	order number of the primary exergy carrier immediately extracted from nature

Superscripts

·	a dot above the symbol denotes the quantity related to the time unit
*	cumulative quantity

Abbreviations

CExC	cumulative consumption of primary exergy
CExE	cumulative exergy efficiency
CExL	cumulative exergy loss
HP-plant	heat-and-power plant

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